ANALYSIS OF DELAY FLUCTUATIONS IN TWO-WAY TIME TRANSFER EARTH STATIONS

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Abstract

The delay fluctuations in earth stations have become the main source of instability that degrades the accuracy of two-way satellite time and frequency transfer. We had installed a satellite simulator system on an earth station for measuring the variations of signal path delays in the station.

The purpose of this paper is to analyze delay variations associated with the environmental temperature. With the data collected over 2 months, we observed that the long-term and short-term temperature variations have contributed different influences to the measured delay value of the earth station. Hence, we propose a method to calculate the related variable by combining the temperature data, and its 1st and 2nd differential values with different weighting coefficients. The result shows a possibility of finding a high correlation between the calculated variable and the delay data. The calculated variable can be used to compensate the delay for their fluctuations.

INTRODUCTION

Two Way Satellite Time and Frequency Transfer (TWSTFT) has become one of the major techniques to compare atomic time scales and primary clocks over long distances. As more and more timekeeping institutes use very stable maser clocks as their references, the diurnal fluctuations of about several hundred picoseconds are present on the continuous or hourly two-way time transfer data **[1,2]**. In order to achieve the better stability, we need to improve the two-way system further.

The delay fluctuations in earth stations are the main source of instability that degrades the accuracy of two-way satellite time and frequency transfer. The method to measure the transmission and reception path delays of the station was first described by Dr. Gerrit de Jong **[3]**. It is based on a satellite simulator, which is located in front of the antenna dish and simulates the function of the satellite.

The Telecommunication Laboratories (TL) had installed a satellite simulator system (SATSIM) on an unoccupied earth station and demonstrated its capability of measuring the differential path delays, (TX-RX)/2, in our previous work **[4,5]**. The system has been applied to monitor the variations of the earth station delay. The high-resolution data of the SATSIM measurement allowed us to carry out more analysis. In this paper, we will propose a method to analyze the correlation between the SATSIM

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14. ABSTRACT
The delay fluctuations in earth stations have become the main source of instability that degrades the accuracy of two-way satellite time and frequency transfer. We had installed a satellite simulator system on an earth station for measuring the variations of signal path delays in the station. The purpose of this paper is to analyze delay variations associated with the environmental temperature. With the data collected over 2 months, we observed that the long-term and short-term temperature variations have contributed different influences to the measured delay value of the earth station. Hence, we propose a method to calculate the related variable by combining the temperature data, and its 1st and 2nd differential values with different weighting coefficients. The result shows a possibility of finding a high correlation between the calculated variable and the delay data. The calculated variable can be used to compensate the delay for their fluctuations.

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measurements and the temperature data.

SATSIM MEASUREMENT

The satellite simulator system consists of a satellite-simulator, the reference cables, and the switching circuitry **[6]**. It has the capability of calculating the transmission and reception delays through a series of measurement loops, including the sums of cable delays, the sum of transmission and reception delay, and the sum of the reference cable delay and the reception delay. The measurement system is completely controlled by the software of a SATRE modem. A scheduling program on the SATRE modem was adapted to arrange these measurement modes. The whole process will finish within 15 minutes. Finally, we can obtain a set of data every 15 minutes through the automated measurements. Then, we calculate their differential delay of transmission and reception, (TX-RX)/2, which affects the result of TWSTFT. On the TL's earth station, the most of the equipment is located outside, including the up- and down-converters, solid-state power amplifier (SSPA), low-noise amplifiers (LNA), and filters. The SATRE modem is placed in an indoor temperature-controlled room. All of the cables on the station are Andrew SFJ1 cable for its very low temperature coefficient. The sensor for measuring the outside air temperature and relative humidity is located only 1.5 m distant from the antenna dish.

MEASUREMENT DATA

A chip rate coded signal with 2.5 MHz was employed to measure the earth station delay, shown in Figure 1. During those 2 months, the outside temperature varied in the range from 7°C to 30°C. The diurnal delay fluctuations appear obvious. The magnitude is about 700 ps and seems to be related to the daily temperature variations. However, Figure 2 shows that there is no significant correlation between the whole data set of the differential delay and the outside temperature.

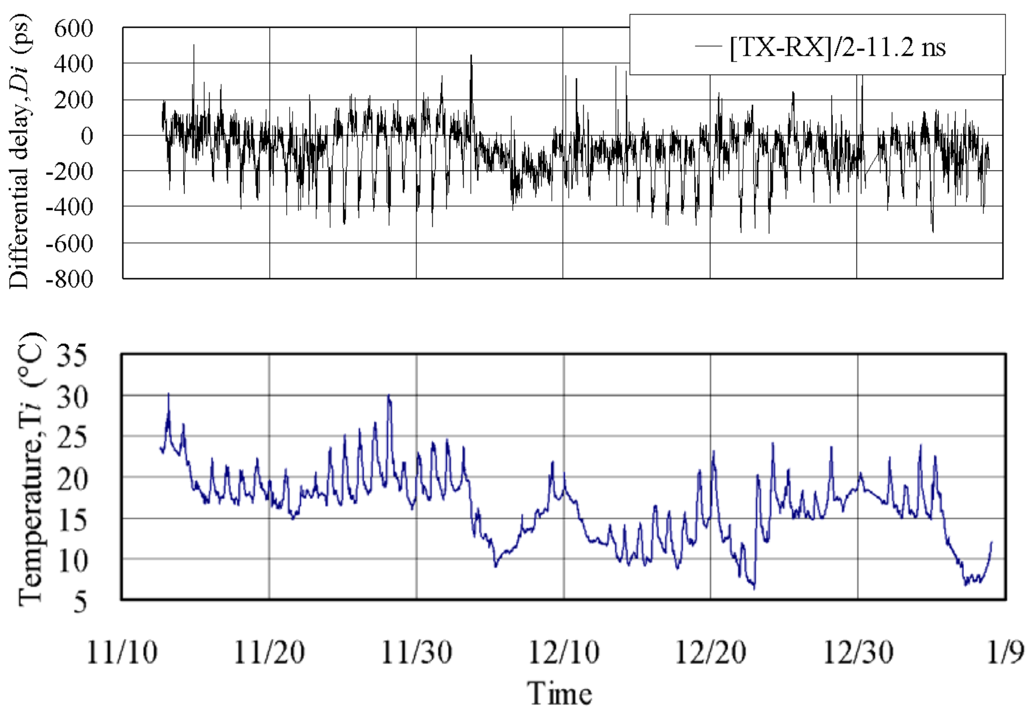

Figure 1. Differential delay of the station and its outside temperature.

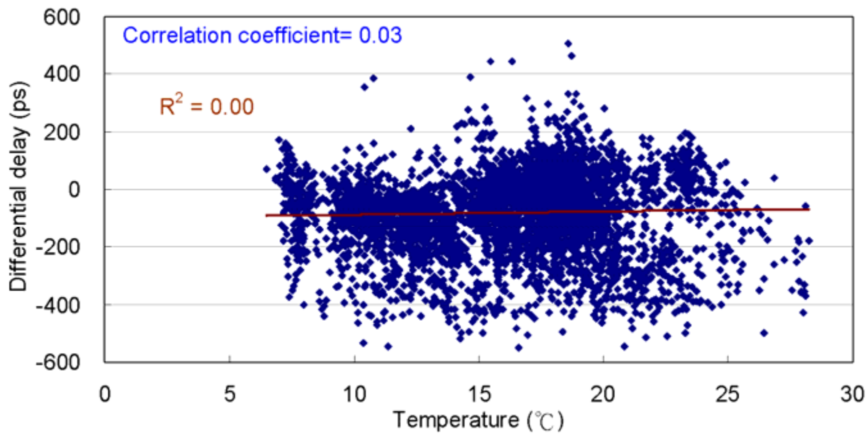

Figure 2. Correlation between the differential delay and the outside temperature.

ANALYSIS METHOD

For the purpose of a meaningful analysis, the relationships between the measurement data should be considered first. Figure 3 shows the possible relationships. The changes of the environmental conditions, including light/shade, wind speed, humidity, and thermal circulation, may affect the TWSTFT earth station. These conditions may cause both the change of path delay and the change in power level of the SSPA, and will certainly affect the two-way time transfer data. Moreover, as a result of using the PN codes, the code tracking error will probably be included **[7]**. In the following analysis, the delay fluctuations of the earth station were measured by the SATSIM system, which also employs the PN codes. Since the variation of temperature data is the most obvious change of the environmental conditions, the following study will be focused on the correlation between the SATSIM measurement data and the observed temperature data.

Because the temperature is always changing and its effects on the station are not so direct, it is hard to find a corresponding table between the measured earth station delay and the environmental temperature. Our method here is to find the response function by using the rate of temperature variations as the key factor.

We need to arrange data into the equally spaced time series, as an example shown on Table 1. The data are separated by a time interval of 15 minutes. The T_i data are the observed temperature; and the D_i data are SATSIM measurements. Their corresponding time tags are the t_i data.

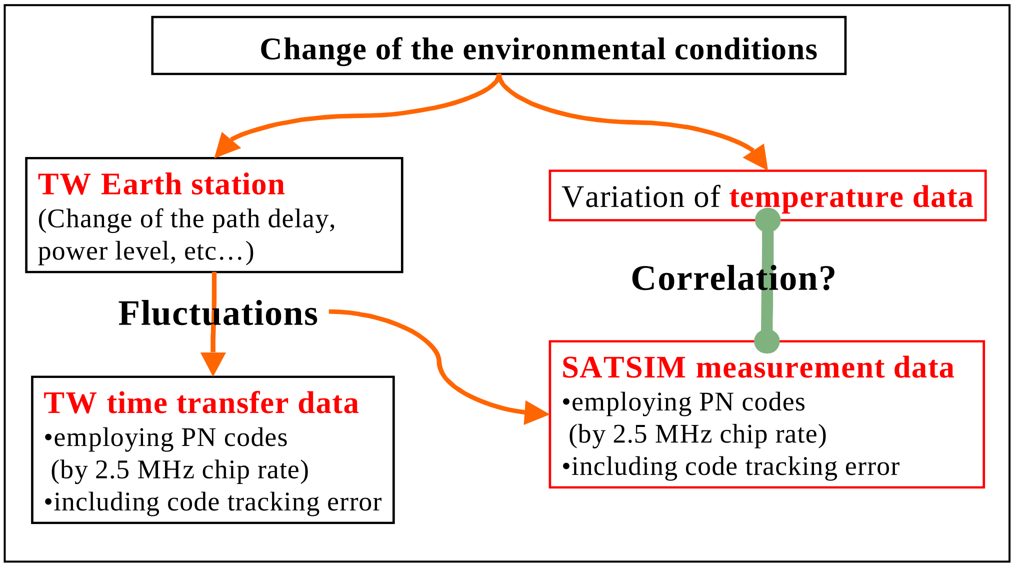

Figure 3. Possible relationships between the measurement data.

Table 1. Data table embedded in a form of the equally spaced time series.

	t*i*	T*i*	D*i*
	Time tag(day)	Temperature (degC)	Differential earth station delay variation (ps)
t*0*	1.00000000	23.9	-10
t*1*	1.01041667	24.2	50
t*2*	1.02083333	24.5	-15
t*3*	1.03125000	24.9	-195
t*4*	1.04166667	25.5	-160
t*5*	1.05208333	25.9	-260
t*6*	1.06250000	26.3	-340
t*7*	1.07291667	25.9	-155
t*8*	1.08333333	26.4	-205

Then, the following formula of calculating the variable X_i with the measured temperature data is considered.

$$X_i = T_i + \sum_{n=1}^{N-i} a_n \frac{T_{i+n} - T_{i-n}}{2n\tau} + \sum_{n=1}^{N-i} b_n \frac{T_{i+n} - 2T_i + T_{i-n}}{(n\tau)^2}$$

X_i are also the data separated by the time interval, τ

$n \leqq i$ is necessary

N is the total number of data point

a_n ,b_n are the weighting coefficients.

The variable X_i is a combination of the observed temperature data, and the 1st and 2nd differential temperature data. Our goal is to adjust weighting coefficients to get the maximum correlation between the calculated variable and the measured earth station delay.

DATA ANALYSIS

At the beginning of analysis, we add a term of the first-order differential temperature data with a time interval of 2 hours, that is, n=8 due to that 15 minutes multiplied by 8 equals to 2 hours. Then,

$$X_i = T_i + a_8 \frac{T_{i+8} - T_{i-8}}{16\tau}$$

A computer program with the "for loop" is used to search for an appropriate value of the weighting coefficient a_8 to get the maximum correlation between the calculated variable (X_i) and the measured earth station delay (D_i). Figure 4 shows the correlation for different values of the weight coefficient a_8. There is a maximum correlation of 0.4128 at $a_8 = -5$. Figure 5 shows the correlation between the differential delay and the calculated variable.

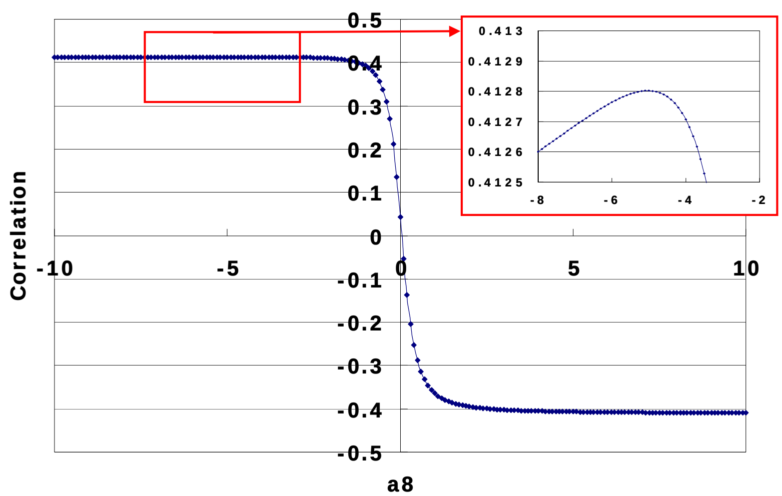

Figure 4. Correlation for different values of the weight coefficient a_8. There is a maximum correlation of 0.4128 at a_8= -5.

Then, we add another term of the second-order differential temperature data with a time interval of 8 hours, that, is n=32 due to that 15 minutes multiplied by 32 equals to 8 hours. Then,

$$X_i = T_i - 5 \cdot \frac{T_{i+8} - T_{i-8}}{16\tau} + b_{32} \frac{T_{i+32} - 2T_i + T_{i-32}}{(32\tau)^2}$$

The same program is used to search for an appropriate value of the weighting coefficient b_{32} to get the

maximum correlation between the calculated variable and the measured earth station delay. Figure 6 shows the correlation for different values of the weight coefficient b_{32}. There is a maximum correlation of 0.66 at b_{32}= 1.8. Figure 7 shows the correlation between the differential delay and the calculated variable.

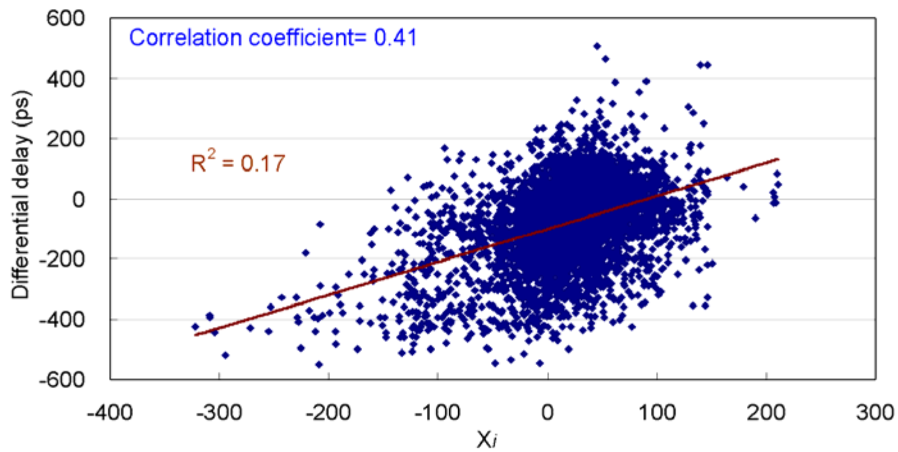

Figure 5. Correlation between the differential delay and the calculated variable (X_i). This calculated variable was calculated by combining the temperature data, and its 1st differential values.

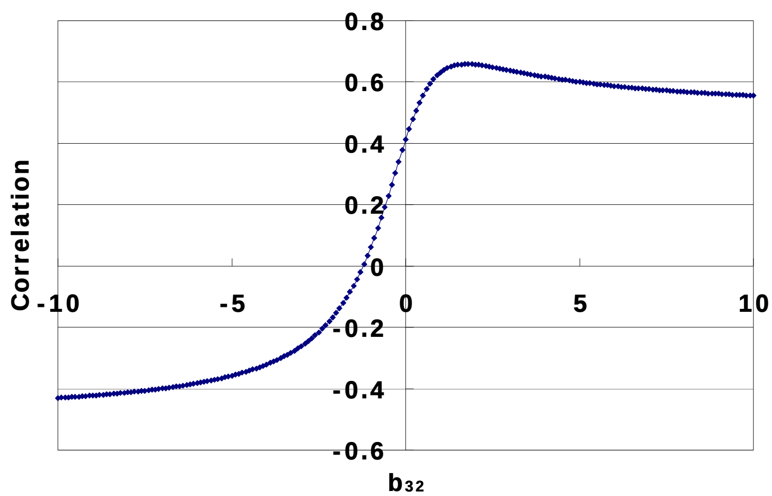

Figure 6. Correlation for different values of the weight coefficient b_{32}. There is a maximum correlation of 0.66 at b_{32}= 1.8.

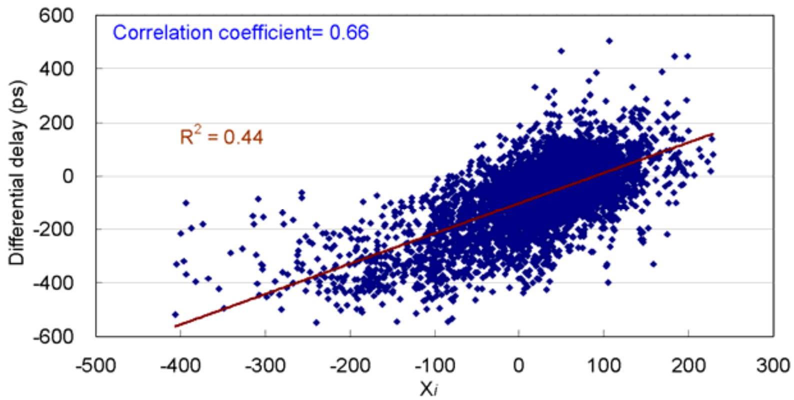

Figure 7. Correlation between the differential delay and the calculated variable (X_i). This variable was calculated by combining the temperature data, and its 1st and 2nd differential values.

The similar procedures are repeated until the weighting coefficients reach its optimal adjustments. A high correlation of 0.73 could be reached by the optimal selection for the weighting coefficients, as below.

$$\mathrm{X}_i = \mathrm{T}_i + \sum_{n=1}^{N-i} a_n \frac{T_{i+n} - T_{i-n}}{2n\tau} + \sum_{n=1}^{N-i} b_n \frac{T_{i+n} - 2T_i + T_{i-n}}{(n\tau)^2}$$

where, a_4=-0.14, a_8=-0.26, a_{16}=-0.17, a_{52}=0.53, a_{104}=-1.3,
b_{32}=0.18, b_{68}=0.26, b_{84}=-0.37, b_{116}=0.87

The selection of the weighting coefficients is not unique. With the addition of a new term of the different time interval, the optimal weight coefficients of the original terms may change. When a representative term is chosen, those terms with the nearby time intervals are negligible for their tiny weights.

Figure 8 shows the correlation between the differential delay and the calculated variable with an optimal selection for the weighting coefficients. A quadratic curve is used to fit the data here. The top of Figure 9 shows the comparison of the differential delay and the calculated variable. The value of the differential delay corresponds to the left coordinate axis; and the value of the calculated variable corresponds to the right coordinate axis. The curve of the differential delay is composed of the blue points. The curve of the calculated variable is composed of the red circles. There are many correspondences between the two curves. The bottom of Figure 9 shows the differential delay modified by the square fit of the variable X_i. The magnitude of the fluctuations of the modified delay is about 400 ps, which is less than the magnitude of the fluctuations of the original delay data.

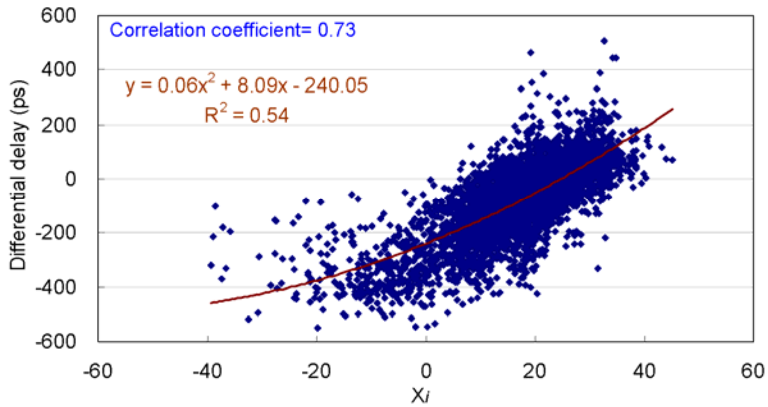

Figure 8. Correlation of 0.73 between the differential delay and the calculated variable with an optimal selection for the weighting coefficients.

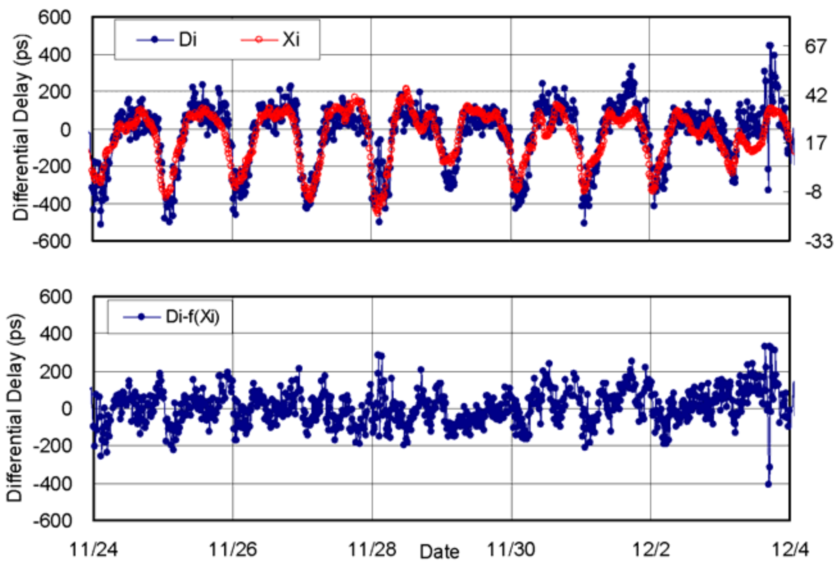

Figure 9. Comparisons. Top: the differential delay (Di) and the calculated variable (Xi). Bottom: the differential delay modified by the square fit of the variable Xi.

Figure 10 shows the time stability (TDEV) analysis for the original differential delay and the modified differential delay. The TDEV of the modified differential delay is shown in the lower curve. Its TDEV stability is below 50 ps for averaging times beyond 2000 seconds. The peak at averaging times ranging from 3×10^4 to 4×10^4 seconds is reduced.

Even through the capability of SATSIM is demonstrated, it is not easy to equip all TW stations with the SATSIM calibration system. It is also hard to put all devices of the station into a well temperature-controlled chamber. We demonstrate that a variable calculated from the observed temperature data can be used to compensate the delay for their fluctuations. The result shows that the compensation is effective, but not perfect.

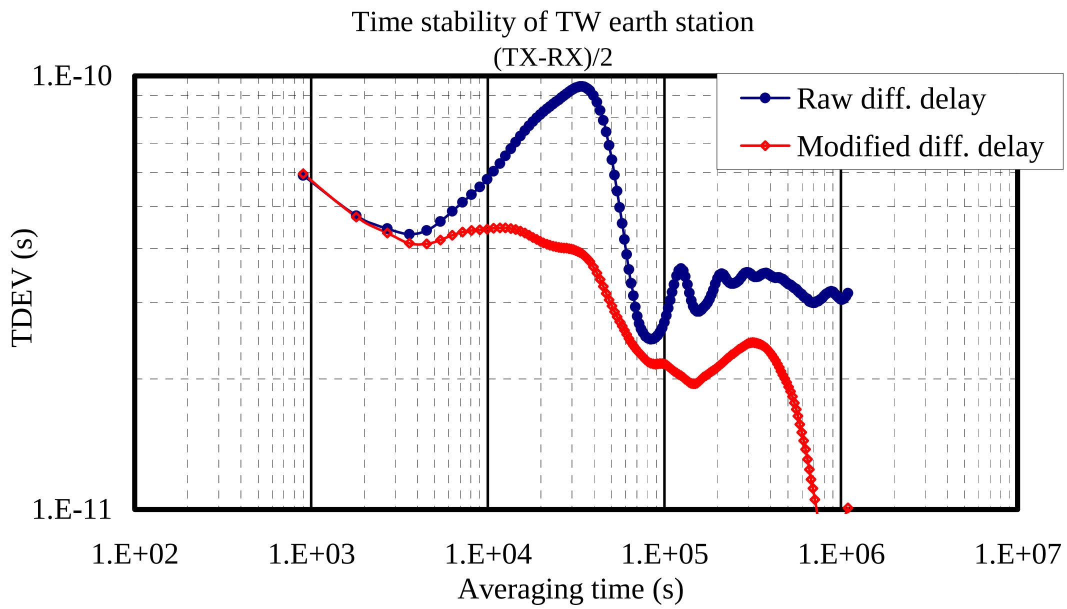

Figure 10. TDEV for the original differential delay and the modified differential delay.

CONCLUSIONS

The SATSIM system was used to monitor the delay variations of TL's earth station. The high-resolution data of the SATSIM measurement allowed us to carry out the analysis. This paper demonstrates a method of analyzing the earth station delay fluctuations associated with the environmental temperature. A new variable was calculated by combining the temperature data, and its 1st and 2nd differential values with different weighting coefficients. A high correlation of 0.73 between the measured earth station delay and the calculated variable could be reached by adjusting the weighting coefficients. The differential delay modified by the calculated variable also shows better time stability. This research may provide useful information for related researches attempting to improve the stability of the time transfer data.

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